

# KMT-2019-BLG-0842Lb: A Cold Planet Below the Uranus/Sun Mass Ratio

YOUN KIL JUNG<sup>1</sup>, ANDRZEJ UDALSKI<sup>2</sup>, WEICHENG ZANG<sup>3</sup>, IAN A. BOND<sup>4</sup>, JENNIFER C. YEE<sup>5</sup>,

AND

MICHAEL D. ALBROW<sup>6</sup>, SUN-JU CHUNG<sup>1,7</sup>, ANDREW GOULD<sup>8,9</sup>, CHEONGHO HAN<sup>10</sup>, KYU-HA HWANG<sup>1</sup>, YOON-HYUN RYU<sup>1</sup>, IN-GU SHIN<sup>1</sup>, YOSHI SHVARTZVALD<sup>11</sup>, SANG-MOK CHA<sup>1,12</sup>, DONG-JIN KIM<sup>1</sup>, HYOUN-WOO KIM<sup>1</sup>, SEUNG-LEE KIM<sup>1,7</sup>, CHUNG-UK LEE<sup>1,7</sup>, DONG-JOO LEE<sup>1</sup>, YONGSEOK LEE<sup>1,12</sup>, BYEONG-GON PARK<sup>1,7</sup>, RICHARD W. POGGE<sup>9</sup>

(KMTNET COLLABORATION)

PRZEMEK MRÓZ<sup>13,2</sup>, MICHAŁ K. SZYMAŃSKI<sup>2</sup>, JAN SKOWRON<sup>2</sup>, RADEK POLESKI<sup>2,9</sup>, IGOR SOSZYŃSKI<sup>2</sup>, PAWEŁ PIETRUKOWICZ<sup>2</sup>, SZYMON KOZŁOWSKI<sup>2</sup>, KRZYSZTOF ULACZYK<sup>14</sup>, KRZYSZTOF A. RYBICKI<sup>2</sup>, PATRYK IWANEK<sup>2</sup>, MARCIN WRONA<sup>2</sup>

(OGLE COLLABORATION)

FUMIO ABE<sup>15</sup>, RICHARD BARRY<sup>16</sup>, DAVID P. BENNETT<sup>16,17</sup>, APARNA BHATTACHARYA<sup>16,17</sup>, MARTIN DONACHIE<sup>18</sup>, HIROSAME FUJII<sup>15</sup>, AKIHIKO FUKUI<sup>19,20</sup>, YUKI HIRAO<sup>21</sup>, YOSHITAKA ITOW<sup>15</sup>, YUKEI KAMEI<sup>15</sup>, IONA KONDO<sup>21</sup>, NAOKI KOSHIMOTO<sup>22,23</sup>, MAN CHEUNG ALEX LI<sup>18</sup>, YUTAKA MATSUBARA<sup>15</sup>, SHOTA MIYAZAKI<sup>21</sup>, YASUSHI MURAKI<sup>15</sup>, MASAYUKI NAGAKANE<sup>21</sup>, CLÉMENT RANC<sup>16</sup>, NICHOLAS J. RATTENBURY<sup>18</sup>, YUKI SATOH<sup>21</sup>, HIKARU SHOJI<sup>21</sup>, HARUNO SUEMATSU<sup>6</sup>, DENIS J. SULLIVAN<sup>24</sup>, TAKAHIRO SUMI<sup>21</sup>, DAISUKE SUZUKI<sup>25</sup>, PAUL J. TRISTRAM<sup>26</sup>, TAKEHARU YAMAKAWA<sup>15</sup>, TSUBASA YAMAMWAKI<sup>21</sup>, ATSUNORI YONEHARA<sup>27</sup>

(THE MOA COLLABORATION)

<sup>1</sup>*Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea*

<sup>2</sup>*Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warszawa, Poland*

<sup>3</sup>*Department of Astronomy and Tsinghua Centre for Astrophysics, Tsinghua University, Beijing 100084, China*

<sup>4</sup>*Institute of Natural and Mathematical Science, Massey University, Auckland 0745, New Zealand*

<sup>5</sup>*Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA*

<sup>6</sup>*University of Canterbury, Department of Physics and Astronomy, Private Bag 4800,  
Christchurch 8020, New Zealand*

<sup>7</sup>*Korea University of Science and Technology, Korea, (UST), 217 Gajeong-ro, Yuseong-gu,  
Daejeon, 34113, Republic of Korea*

<sup>8</sup>*Max-Planck-Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany*

<sup>9</sup>*Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH  
43210, USA*

<sup>10</sup>*Department of Physics, Chungbuk National University, Cheongju 28644, Republic of  
Korea*

<sup>11</sup>*Department of Particle Physics and Astrophysics, Weizmann Institute of Science,  
Rehovot 76100, Israel*

<sup>12</sup>*School of Space Research, Kyung Hee University, Yongin, Kyeonggi 17104, Republic of  
Korea*

<sup>13</sup>*Division of Physics, Mathematics, and Astronomy, California Institute of Technology,  
Pasadena, CA 91125, USA*

<sup>14</sup>*Department of Physics, University of Warwick, Gibbet Hill Road, Coventry,  
CV4 7AL, UK*

<sup>15</sup>*Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601,  
Japan*

<sup>16</sup>*Code 667, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

<sup>17</sup>*Department of Astronomy, University of Maryland, College Park, MD 20742, USA*

<sup>18</sup>*Department of Physics, University of Auckland, Private Bag 92019, Auckland, New  
Zealand*

<sup>19</sup>*Department of Earth and Planetary Science, Graduate School of Science, The University  
of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

<sup>20</sup>*Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain*

<sup>21</sup>*Department of Earth and Space Science, Graduate School of Science, Osaka University,  
Toyonaka, Osaka 560-0043, Japan*

<sup>22</sup>*Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

<sup>23</sup>*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*

<sup>24</sup>*School of Chemical and Physical Science, Victoria University, Wellington, New Zealand*

<sup>25</sup>*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa 252-5210, Japan*

<sup>26</sup>*University of Canterbury Mt. John Observatory, P.O. Box 56, Lake Tekapo 8770, New Zealand*

<sup>27</sup>*Department of Physics, Faculty of Science, Kyoto Sangyo University, Kyoto 603-8555, Japan*

## ABSTRACT

With  $q = (4.09 \pm 0.27) \times 10^{-5}$ , KMT-2019-BLG-0842Lb is the second cold planet with planet-host mass ratio  $q$  below that of Uranus relative to the Sun ( $q = 4.37 \times 10^{-5}$ ), the first having been discovered only in 2018. Hence, such cold, sub-Uranus-ratio planets are probably not rare. We discuss possible improvements in the search for these planets. The Bayesian estimates for the host mass, planet mass, system distance, and planet-host projected separation are  $M_{\text{host}} = 0.76 \pm 0.40 M_{\odot}$ ,  $M_{\text{planet}} = 10.3 \pm 5.5 M_{\oplus}$ ,  $D_L = 3.3 \pm 1.3 \text{ kpc}$ , and  $a_{\perp} = 3.3 \pm 1.4 \text{ AU}$ , respectively. The blended light is plausibly due to the host star, an identification that could be tested by high resolution images taken during the next (2020) bulge season.

*Subject headings:* gravitational lensing: micro

## 1. Introduction

For the first 15 years of microlensing planet detections, there was no clear evidence for “cold planets” (i.e., beyond the snow line) with mass ratios below that of Uranus ( $q = 4.37 \times 10^{-5}$ ), neither in our Solar System nor in other systems. There are of course several cold, low-mass bodies in the outer Solar System, but these are more than 10 times less massive than the smallest terrestrial planet (Mercury). The same applies to Ceres, which

lies approximately on the snow line. Such bodies likely form by a distinct mechanism relative to planets, and they were therefore reclassified as “dwarf planets” by the IAU.

Cold, low-mass planets in exo-systems can only be detected by microlensing (Bennett & Rhie 1996; Beaulieu et al. 2006; Gould et al. 2006). Yet, by 2017, no such planets were unambiguously detected with mass ratios below  $q = 4.7 \times 10^{-5}$  (Udalski et al. 2018)<sup>1</sup>.

In principle, the lack of such detections could have been due to one of the following four causes: (1) poor sensitivity of microlensing searches to such planets; (2) extreme rarity (or complete absence) of such planets in nature; (3) adverse fluctuation of small-number statistics; or (4) some combination of these. Suzuki et al. (2016) showed that there is a break in the power-law distribution (in  $q$ ) below some threshold, estimated roughly at  $q_{\text{br}} \sim 1.7 \times 10^{-4}$ , arguing in particular that their MOA-based planet sample had significant sensitivity below the lowest- $q$  detections. Udalski et al. (2018) confirmed that if the planets  $q < 1 \times 10^{-4}$  were modeled as a power law, its slope was rising with  $q$ , in contrast to the well-established falling power law at higher  $q$ . Moreover, they showed that four of the seven planets that they analyzed would have been detected even if their mass ratios had been below  $q = 3 \times 10^{-5}$ , and one of these would have been detected even at  $q = 2 \times 10^{-6}$ , i.e., below the Earth/Sun mass ratio. Jung et al. (2019) argued that the dearth of planets below  $q = 4.7 \times 10^{-5}$  was due either to a break in the mass-ratio function at  $q_{\text{br}} \simeq 5.6 \times 10^{-5}$  or a “pile-up” of planets near the Neptune-mass-ratio threshold.

With mass ratio  $q = (1.8 \pm 0.2) \times 10^{-5}$ , KMT-2018-BLG-0029 was the first reported planet that lay clearly below the previous apparent Uranus/Sun mass-ratio threshold (Gould et al. 2019). It provided proof for the existence of such planets, but a single detection gives very limited information on their frequency. Gould et al. (2019) reviewed the history of the (by then, nine)  $q < 1 \times 10^{-4}$  planet detections, and concluded that with the advent of regular observations of the Korea Microlensing Telescope Network (KMTNet, Kim et al. 2018a,b,c) in 2016, the rate of such detections was increasing, and that it should be possible to probe the frequency of such low-mass planets within a few years.

Here, we report the discovery of KMT-2019-BLG-0842Lb. At  $q = (4.09 \pm 0.27) \times 10^{-5}$ , it is the second microlensing planet below the Uranus/Sun mass ratio. It therefore plays an

---

<sup>1</sup>Within their sample of seven  $q < 1 \times 10^{-4}$  microlensing planets, OGLE-2016-BLG-1195, had the lowest mass ratio  $q = (4.7 \pm 0.5) \times 10^{-5}$ . Udalski et al. (2018) took the average from two groups who had made independent parameter determinations using disjoint data sets:  $q = [(4.2 \pm 0.7) \& (5.5 \pm 0.8)] \times 10^{-5}$  from Bond et al. (2017) and Shvartzvald et al. (2017), respectively. Udalski et al. (2018) excluded OGLE-2017-BLG-0173 from their sample because its solution was ambiguous by a factor 2.5 ( $2.48 \pm 0.24$  versus  $6.4 \pm 1.0$ )  $\times 10^{-5}$  at  $\Delta\chi^2 = 3.5$  (Hwang et al. 2018).

important role in accumulating statistics in this poorly probed regime.

## 2. Observations

KMT-2019-BLG-0842, (R.A., Decl.)<sub>J2000</sub>=(17:53:50.03, −29:52:38.78), corresponding to  $(l, b) = (+0.11, -2.02)$ , was discovered by the KMT alert-finder system (Kim et al. 2018d) and announced as a microlensing candidate on the KMTNet website<sup>2</sup> at UT 02:39 on 16 May 2019, about six days before the event reached its peak. The event was independently found by the Optical Gravitational Lensing Experiment (OGLE, Udalski et al. 2015) and the Microlensing Observations in Astrophysics (MOA, Bond et al. 2004) collaborations at UT 19:30 on 18 May 2019 as OGLE-2019-BLG-0763 and at UT 07:02 on 24 May 2019 as MOA-2019-BLG-232, respectively.

KMTNet is comprised of three identical 1.6m telescopes equipped with ( $2^\circ \times 2^\circ$ ) cameras, located at Cerro Tololo InterAmerican Observatory (KMTC), the South African Astronomical Observatory (KMTS), and the Siding Springs Observatory (KMTA) (Kim et al. 2016). KMT-2019-BLG-0842 lies in the overlapping KMT fields BLG02 and BLG42, each of which is observed at a nominal cadence of  $\Gamma = 2 \text{ hr}^{-1}$ . However, both fields were observed at an adjusted cadence of  $\Gamma = 3 \text{ hr}^{-1}$  from KMTS and KMTA prior to 15 June, i.e., until more than three weeks after the peak of the event. Hence, the effective cadence was  $\Gamma = 4 \text{ hr}^{-1}$  from KMTC and  $\Gamma = 6 \text{ hr}^{-1}$  from KMTS and KMTA. The observations were primarily conducted in the  $I$  band, but every tenth such observation was matched by a  $V$ -band observation in order to measure the source color.

OGLE observed this event (in field BLG501) in 2019 at a cadence  $\Gamma = 1 \text{ hr}^{-1}$  from its 1.3m telescope with  $1.4 \text{ deg}^2$  camera at Las Campanas Observatory in Chile. OGLE observations were also primarily conducted in the  $I$  band.

The light curve derived from the KMTNet and OGLE observations is shown in Figure 1. The KMTNet data were reduced using pySIS (Albrow et al. 2009), which is a variant of difference image analysis (DIA, Tomaney & Crotts 1996; Alard & Lupton 1998). The OGLE data were reduced using another variant of DIA (Woźniak 2000). The relatively brief ( $\sim 15 \text{ hr}$ ) planetary anomaly was announced by W. Zang at UT 19:56 on 26 May 2019 (JD' = JD-2450000 = 8630.33), but by this time the anomaly was already over, and so no followup observations of the anomaly resulted from the announcement.

MOA observed this object at a cadence of  $\Gamma = 4 \text{ hr}^{-1}$  using its 1.8m telescope at Mt.

---

<sup>2</sup><http://kmtnet.kasi.re.kr/~ulens>

John, New Zealand, which is equipped with a 2.2 deg<sup>2</sup> camera. However, conditions were poor on the night of the anomaly. The resulting observations therefore do not constrain the characteristics of the planet, although they do qualitatively confirm its existence. We therefore do not include these data in the primary fit, but rather use them to illustrate this confirmation (Figure 2). MOA observations were mainly taken using a broad  $R/I$  filter.

### 3. Light Curve Analysis

With the exception of the short anomaly peaking at  $t_{0,\text{anom}} = 8627.85$ , KMT-2019-BLG-0842 has the general appearance of a Paczyński (1986) single-lens single-source (1L1S) event, which is characterized by three geometric parameters ( $t_0, u_0, t_E$ ), respectively the time of maximum, the impact parameter (in units of the Einstein radius  $\theta_E$ ), and the Einstein radius crossing time,

$$t_E \equiv \frac{\theta_E}{\mu_{\text{rel}}}; \quad \theta_E^2 \equiv \kappa M \pi_{\text{rel}}; \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} \simeq 8.14 \frac{\text{mas}}{M_\odot}, \quad (1)$$

where  $M$  is the lens mass and  $(\pi_{\text{rel}}, \mu_{\text{rel}})$  are the lens-source relative parallax and proper motion, respectively. From visual inspection,  $t_0 \simeq 8625.91$  and the full width at half maximum (FWHM) of the light curve is 1.0 days. The event peaks at either high magnification or very high magnification (depending on the blending, which is difficult to estimate by eye), and in either case  $u_0 \ll 1$ , so  $t_{\text{eff}} \equiv u_0 t_E = \text{FWHM}/\sqrt{12} \simeq 0.29$  day. Hence (e.g., Gould & Loeb 1992), the source almost certainly passes at an angle

$$\alpha = \tan^{-1} \frac{t_{\text{eff}}}{t_{0,\text{anom}} - t_0} = \tan^{-1} 0.149 = 0.148, \quad (2)$$

or 8.5°, relative to the binary axis. The fact that the anomaly is relatively short, even though the source crosses the caustic structure at such an acute angle  $\alpha$ , suggests a low mass ratio,  $q$ . A similar inference can be drawn from the fact that there is no noticeable anomaly over the high (or very high) magnification peak. That is, both effects tend to indicate a small, resonant (or near-resonant) caustic. However, detailed modeling is required to proceed further.

#### 3.1. Binary Lens (2L1S) Analysis

We model the light curve as a 2L1S event with seven non-linear parameters  $(t_0, u_0, t_E, s, q, \alpha, \rho)$ , where  $s$  is the projected separation between the binary components (normalized to  $\theta_E$ ),

$\rho \equiv \theta_*/\theta_E$ , and  $\theta_*$  is the angular source radius. Notwithstanding the above estimate of  $\alpha$ , we conduct a broad grid search in the parameters  $s$ ,  $q$ , and  $\alpha$ , in which  $(s, q)$  are held fixed and the remaining five parameters are allowed to vary in a Markov chain Monte Carlo (MCMC). The three parameters  $(t_0, u_0, t_E)$  are seeded at their Paczyński (1986) values,  $\rho$  is seeded at  $10^{-3}$ , and  $\alpha$  is seeded at six values drawn uniformly from the unit circle. There are two flux parameters  $(f_{s,i}, f_{b,i})$  for each observatory  $i$ , which are fit by linear regression to the observed flux  $F_i(t)$  for each model, according to  $F_i(t) = f_{s,i}A(t) + f_{b,i}$ . These are identified with the “source” and “blend” flux, respectively.

We find only two local minima in the resulting  $(s, q)$  map, which we then further refine by allowing all seven parameters to vary in the MCMC. Finally, these converge to  $(s, q) = (0.98, 4.1 \times 10^{-5})$  and  $(s, q) = (1.06, 3.9 \times 10^{-5})$ . See Table 1. These solutions are actually quite similar in all of their parameters, and in particular both agree with the naive estimate for  $\alpha$  given above. However, the “wide” solution ( $s > 1$ ) is disfavored relative to the “close” solution ( $s < 1$ ) by  $\Delta\chi^2 = 176$ . Furthermore, the “wide” solution has clear systematic residuals. See Figure 3. Hence, we exclude the “wide” solution. The caustic geometries for both the “close” and “wide” solutions are shown in Figure 4.

We investigate whether the microlens parallax vector  $\boldsymbol{\pi}_E$  (Gould 1992, 2000, 2004) can be meaningfully constrained, but we find that it cannot.

### 3.2. Binary Source (1L2S) Analysis

Gaudi (1998) pointed out that a short-lived “bump” on an otherwise normal Paczyński (1986) lightcurve could in principle be produced by a second source (1L2S) rather than a second lens (2L1S). This is of particular concern when (as in the present case) the “bump” does not exhibit any obvious caustic structure. Our 1L2S model has eight nonlinear parameters:  $2 \times (t_0, u_0, \rho)$  for the two sources, plus a common Einstein timescale  $t_E$  and the  $I$ -band flux ratio between the two sources,  $q_{F,I}$ . See Table 2.

However, we find that 1L2S provides a poor fit to the data compared to 2L1S, with  $\Delta\chi^2 = \chi^2(1L2S) - \chi^2(2L1S) = 495$ . Moreover, the solution is unphysical in the sense that the flux ratio is  $q_{F,I} \simeq 0.013$  while the normalized sources sizes  $(\rho_1, \rho_2)$  are of the same order<sup>3</sup>. See Table 2 and Figure 3. Hence, 1L2S is excluded.

---

<sup>3</sup>Strictly speaking,  $\rho_1$  is poorly constrained by the fit, but it has a strict upper limit  $\rho_1 < u_{0,1} = 56 \times 10^{-4}$ , which implies the same unphysicality.

#### 4. Color-Magnitude Diagram and Einstein Radius

Although the planetary anomaly does not exhibit obvious caustic features, the results in Table 1 show that the normalized source size  $\rho$  is reasonably well measured<sup>4</sup>. This implies that we can estimate  $\theta_E = \theta_*/\rho$  provided that we can determine  $\theta_*$ . Indeed, while the  $1\sigma$  error in  $\rho$  is relatively large, there is a very strong,  $3\sigma$ , upper limit  $\rho < 5.7 \times 10^{-4}$ , which will place interesting physical constraints on the system, as we discuss below.

We follow the standard approach (Yoo et al. 2004) of measuring  $\theta_*$  by placing the source on an instrumental color-magnitude diagram (CMD). See Figure 5. For this purpose, we reduce the KMTCC42  $V$  and  $I$  data using pyDIA, which yields field-star and light-curve photometry on the same system. Using this instrumental system, we find source and red-clump-centroid positions of  $[(V - I), I]_s = (2.38, 21.73) \pm (0.03, 0.01)$  and  $[(V - I), I]_{cl} = (2.43, 16.04) \pm (0.03, 0.07)$ , respectively, and hence an offset of  $\Delta[(V - I), I] = (-0.05, 5.69) \pm (0.04, 0.07)$ . We adopt  $[(V - I), I]_{cl,0} = (1.06, 14.44)$  (Bensby et al. 2013; Nataf et al. 2013). We do not assign an error to this determination but rather add 5% error in quadrature to the final result for all aspects of the method. We then obtain  $[(V - I), I]_{s,0} = [(V - I), I]_{cl,0} + \Delta[(V - I), I] = (1.01, 20.13) \pm (0.04, 0.07)$ . That is, assuming that the source is at the mean distance to the bulge, it has  $[(V - I)_0, M_I]_s \simeq (1.0, 5.6)$ , which is typical of early K dwarfs.

We then convert from  $V/I$  to  $V/K$  using the  $VIK$  color-color relations of Bessell & Brett (1988) and then apply the color/surface-brightness relations of Kervella et al. (2004) to obtain (after adding 5% error),

$$\theta_* = 0.416 \pm 0.031 \mu\text{as}. \quad (3)$$

We can then obtain “naive” estimates for  $\theta_E$  and  $\mu_{\text{rel}}$ ,

$$\theta_E = \frac{\theta_*}{\rho} = 0.96 \pm 0.22 \text{ mas}; \quad \mu_{\text{rel}} = 8.0 \pm 1.8 \text{ mas yr}^{-1} \quad (\text{naive}). \quad (4)$$

We refer to these two estimates as “naive” because, as discussed in Section 5, in the present case the proper evaluation of these quantities should be their Bayesian posteriors.

These values of  $\theta_E$  and  $\mu_{\text{rel}}$  strongly imply that the lens lies in the disk. That is, from the definition of  $\theta_E$  (Equation (1)),  $\pi_{\text{rel}} = 0.12 \text{ mas} (\theta_E / \text{mas})^2 / (M/M_\odot)$ . Thus, if we adopt the best-fit value of  $\theta_E$  and also take account of the fact that lenses significantly more massive than the Sun would easily be visible, then we would infer  $\pi_{\text{rel}} \gtrsim 0.12 \text{ mas}$ , i.e., lens distance  $D_L \lesssim 4 \text{ kpc}$ . Because the error in  $\theta_E$  is large (due primarily to the large error in  $\rho$ ), we

---

<sup>4</sup>This was also the case for the low- $q$  planetary event OGLE-2016-BLG-1195 (Bond et al. 2017; Shvartzvald et al. 2017)



must also consider how smaller values of  $\theta_E$  (i.e., below the best-fit value) would affect this argument. However, as mentioned above, the errors in  $\rho$  are highly asymmetric, so there is a very hard lower limit  $\theta_E > 0.65$  mas. This somewhat relaxes the above argument, but still requires  $\pi_{\text{rel}} \gtrsim 0.06$  mas, which still puts the lens in the disk. We note that the best-fit proper motion is also very typical of disk lenses, although it would not be inconsistent with a bulge lens.

## 5. Physical Parameter Estimates

Because the microlens parallax  $\pi_E$  is not measured, one cannot directly infer the lens mass  $M = \theta_E / \kappa \pi_E$  and lens-source relative parallax  $\pi_{\text{rel}} = \theta_E \pi_E$  from the microlensing data. We therefore make a Bayesian analysis by incorporating priors from a Galactic model. In fact, the situation is somewhat more complicated than usual because the measurement error on the normalized source radius  $\rho$  is large and its distribution is asymmetric. Moreover,  $\rho$  is correlated with the planet-host mass ratio  $q$ . Thus, in sharp contrast to the usual case, the posterior estimate of this (seemingly) pure microlensing-light-curve parameter  $q$  is actually affected by the Galactic priors.

The fundamental features of the Galactic model and the Bayesian procedures are the same<sup>5</sup> as those presented by Jung et al. (2018). Here, we focus on describing what is different for the present case.

As usual, we incorporate constraints on both  $t_E$  and  $\theta_E$  from the light-curve modeling and CMD. And, as usual, we weight the simulated events by  $W_{t_E} = \exp[-(t_E - t_{E,\text{best}})^2 / 2\sigma_{t_E}^2]$ , where  $t_E$  is the Einstein timescale of the simulated event and  $(t_{E,\text{best}}, \sigma_{t_E})$  are the values from Table 1. However, we do not, as would usually be the case, incorporate the  $\theta_E$  measurement in a similar manner.

Rather, we first evaluate a function  $\Delta\chi^2(\rho)$  by running MCMCs at a series of fixed values of  $\rho$ . See Figure 6. Then, for each simulated event, we evaluate  $\theta_E = \sqrt{\kappa M \pi_{\text{rel}}}$  from the simulated lens mass and the simulated lens and source distances. And we evaluate  $\theta_*$  by drawing randomly from a Gaussian defined by Equation (3). We then evaluate  $\rho = \theta_*/\theta_E$  and finally determine the weight  $W_{\theta_E} = \exp[-\Delta\chi^2(\rho)/2]$ .

The Bayesian analysis then mostly continues by the usual procedures, but with one major exception. In Figure 6, we show the best-fit value of  $q$  and its  $1\sigma$  error bar for each

---

<sup>5</sup>We note that Jung et al. (2018) do not specify their upper-mass cutoff for the mass function. For completeness, we note that this cutoff is  $63 M_\odot$ .

fixed- $\rho$  MCMC that was carried out above to evaluate  $\Delta\chi^2(\rho)$ . Over the region of principal interest,  $3 \lesssim \rho/10^{-4} \lesssim 5$ , this shows a logarithmic (power-law) gradient  $d\log q/d\log \rho \simeq -0.2$ . This gradient is present because the models account for the observed duration of the “bump” by a combination of  $q$  and  $\rho$ : for relatively large  $q$ , this duration is explained by the width of the ridge, but with decreasing  $q$  it must be increasingly explained by larger  $\rho$ . For most events, such a gradient would play a very small role because  $\rho$  would be well determined. However, in the present case, the error in  $\rho$  is large, so that the error in  $q$  induced by this correlation is comparable to the scatter in  $q$  at fixed  $\rho$ . Therefore, to properly evaluate the *posterior* value of  $q$ , we should incorporate the correlation into the Bayesian analysis.

We do so by evaluating  $q$  separately for each simulated event in the MCMC. We first find  $\rho$  (as above). We then find  $q(\rho)$  and  $\sigma_q(\rho)$  from a table that corresponds to Figure 6 and then draw  $q$  randomly from a Gaussian described by these two values. This value of  $q$  is then used both to evaluate the planet mass for the simulated event  $m_p = qM_{\text{host}}$  and to find the posterior distribution of  $q$  itself.

The results of the Bayesian analysis are shown in Table 3 and Figure 7. Notwithstanding the above argument that the lens must lie in the disk, we formally consider both bulge and disk lenses within the Bayesian analysis. However, as expected, we find that the chance that the lens is in the bulge is very low,  $< 1\%$ .

### 5.1. Does the Lens Account for the Blended Light?

The best-fit position of the blended light  $[(V-I), I]_b = (1.68, 19.84)$  lies  $\Delta[(V-I), I]_b = [(V-I), I]_b - [(V-I), I]_{\text{cl}} = (-0.75, 3.80)$  from the clump on the CMD. We discuss the error bars on this position further below.

The  $I$ -band brightness offset  $\Delta I_b = 3.80$  is consistent with the lens mass and distance ranges derived from the Bayesian analysis above, as summarized in Figure 7. For example, suppose that the lens were near the median of the posterior distance distribution, at  $D_L = 3.3 \text{ kpc}$ . It would then be at about  $z \simeq -0.1 \text{ kpc}$  below the plane, and so plausibly behind about half the dust toward the bulge, which has  $[E(V-I), A_I] = (1.28, 1.50)$  (Nataf et al. 2013). This would imply an absolute magnitude  $M_I = 14.45 + 3.80 - 1.50/2 - 5 \log(330) \simeq 4.9$ , corresponding roughly to an  $M = 0.85 M_\odot$  star, which is quite compatible with the Bayesian host-mass distribution. Such a star would have (depending on its metallicity) roughly  $(V-I)_0 \sim 0.85$ , and therefore would be  $\Delta(V-I) = 0.85 - 1.06 - 1.28/2 \simeq -0.85$  mag bluer than the clump. Given the measurement errors (which we estimate just below), this is quite compatible with the “observed” offset:  $-0.75$  mag bluer than the clump.

The baseline object is quite faint in the  $V$  band,  $V_{\text{base}} = 21.43$ . It is therefore barely detected, and hence the error in magnitudes is large. The contribution from the source to this baseline light is known quite precisely, so from a conceptual point of view, we should consider the errors in the point-spread-function (PSF) modeling of the remaining blended light  $V_b = 21.52$ . The error in this estimate is comprised of three distinct components: Poisson errors from finite photon statistics; systematic errors from the PSF modeling photometry program, operating under the assumption that the background is smooth; and statistical errors due to the fact that a mottled distribution of unresolved stars contributes significantly to the background.

Based on photon statistics, we estimate the first error as 0.19 mag. Because the PSF photometry program is relatively complex, it is difficult to reliably estimate the systematic errors. Hence, we ignore these for the moment. To estimate the errors due to the mottled background, we apply the approach of Ryu et al. (2019), i.e., modeling the Holtzman et al. (1998) luminosity function adjusted for the local surface brightness of the bulge and the local extinction. In fact, the mottled background results in correlated errors between the  $I$  and  $V$  band measurements because there can be an excess or a “hole” in this background of stars that are predominantly redder than the apparent blend star. Hence, an excess at the location of the event would cause the apparent blend to appear brighter and redder, while a “hole” in the background would make it appear fainter and bluer.

Based on the surface density of clump stars (Nataf et al. 2013; D. Nataf, 2019, private communication), we find a normalization factor of 2.41 relative to Baade’s Window. We adopt  $[E(V - I), A_I] = (1.28, 1.50)$  from Nataf et al. (2013), and we evaluate using a  $1.5''$  FWHM seeing disk. We find that (from this effect alone), there is a 16% probability that the blend has been made to appear at least 0.20 mag bluer than it is, as well as a 16% probability that the blend has been made to appear at least 0.28 mag redder than it is. Hence, combining the two effects that we can quantitatively evaluate, the color error is at least  $\pm 0.28$  mag.

We should also ask how well the source is astrometrically aligned with the baseline object. We measure the position of the source and baseline object relative to the KMTC42 template and find in (west, north)  $0.4''$  pixel coordinates, that the baseline object lies  $(0.32, -0.12)$  pixels, or  $(0.13'', -0.05'')$ , i.e., west and south of the source. Because the source position is derived from difference images (which removes both the resolved and unresolved backgrounds) and because the source is highly magnified in these images, the errors in the source position are negligible relative to the errors in the baseline object. Hence we ignore them.

The baseline-object position errors come from the same three sources as its photometric

errors. The astrometry is done in  $I$ -band, so we evaluate these errors in this band. We again only evaluate the errors due the first and third effects. We estimate the fractional astrometric error (relative to the Gaussian half width  $\sigma = \text{FWHM}/\sqrt{\ln 256}$ ) as equal to the fractional photometric error,  $(\ln 10/2.5)\sigma_I$ . That is,  $\sigma_{\text{ast}} = 0.39\sigma_I \text{FWHM} \rightarrow 0.6''\sigma_I$ . We find that the photon-error contribution to  $\sigma_I$  is 0.14 mag.

Next, we consider the error due to the mottled background. If we evaluate this without constraints, we find  $\sigma_I = 0.6$ . However, if we restrict to cases where the background produces a “hole” then  $\sigma_I = 0.3$ . Combined, these two sources of error imply  $\sigma_{\text{ast}} = 0.37''$  and  $\sigma_{\text{ast}} = 0.20''$  for the two cases. This is larger than the observed offset. Hence, the blended light is also astrometrically consistent with being due to the lens.

We conclude that the blended light is consistent with being due to the lens. However, we emphasize that there is no strong evidence that it is due to the lens: only that this possibility warrants additional observational investigation.

## 6. Discussion

### 6.1. Very Low Mass-Ratio Planets

KMT-2019-BLG-0842Lb is the second cold planet below Uranus/Sun mass ratio, i.e., the lower limit for such planets in the Solar System. Although it lies only about 7% below this limit, its discovery provides evidence that such planets are not rare. Nevertheless, further discoveries will be necessary to estimate the frequency and characterize the distribution of such planets.

As noted by Ryu et al. (2019), the pace of discovery of relatively low-mass-ratio microlensing planets  $q \leq 1 \times 10^{-4}$  appears to be accelerating since 2015, when KMTNet commenced. The 11 such planets (including KMT-2018-BLG-0029Lb and KMT-2019-BLG-0842Lb) occurred in (2005, 2005, 2007, 2009, 2013, 2015, 2016, 2017, 2018, 2018, 2019). That is, five during the 10 seasons before 2015 and six during the five seasons since. Moreover, the data from the 2019 season have not yet been fully analyzed. If indeed sub-Uranus/Sun planets are reasonably common, we can expect more detections based on this general increased rate.

However, the overall rate of detection of low-mass-ratio planets  $q \leq 1 \times 10^{-4}$  remains relatively low (a little more than one per year) and, within this group, sensitivity to planets definitely declines with decreasing mass ratio  $q$ . Therefore, it is worthwhile to ask what features of these planetary events allowed them to be detected and whether anything can be

done to adjust the search strategy to take advantage of these features.

A notable feature of KMT-2019-BLG-0842Lb is that it appeared in a high-magnification event ( $u_0 = 0.0066$ ;  $A_{\text{max}} = 150$ ), and at very low angle  $\alpha = 0.146$  ( $8.5^\circ$ ) between the source trajectory and the binary axis. That is, the magnification of the underlying 1L1S event at the time of the planetary anomaly was modest:  $A_{\text{anom}} \simeq \sin(\alpha)/u_0 = 22$ . This means that the source would have passed over the same part of the caustic structure if the event had had  $A_{\text{max}} = 22$ ; ( $u_0 = 0.045$ ) and  $\alpha = 90^\circ$ . This is similar to the situations for OGLE-2016-BLG-1195, which had  $|u_0| = 0.053$ ,  $|\alpha| = 55^\circ$ , and a slightly higher mass ratio, and for KMT-2018-BLG-0029, which had  $|u_0| = 0.027$ ,  $|\alpha| = 88^\circ$ , and a substantially lower mass ratio. Thus, at first sight, it seems that such moderate-magnification events provide just as fertile ground to hunt for low-mass planets as high-magnification events (as advocated by Abe et al. 2013). In fact, however, KMT-2019-BLG-0842Lb would have been discovered for values of  $\alpha$  covering most of the unit circle at its actual  $u_0$ , whereas at  $u_0 = 0.045$  the sensitivity would have been restricted to a relatively narrow range of angles.

However, the main feature to note about this low value of  $\alpha$  is that it caused the anomaly to be longer by factor  $\cot \alpha \simeq 7$  relative to an orthogonal transit of the caustic structure. That is, in an orthogonal crossing, the full duration would have been about two hours rather than 15 hours. This is just twice the source-diameter self-crossing time,  $2t_* \equiv 2\rho t_E = 0.9$  hr. Such a short anomaly would have been detected in the actual observations (provided that it did not fall in a gap) because the event was in a high-cadence KMT field, with  $\Gamma = 4\text{--}6$  hr $^{-1}$ . But if it had been in a field with a cadence  $\Gamma = 0.75\text{--}1$  hr $^{-1}$ , then a two-hour anomaly would not have been reliably detected, while a 15-hour anomaly (as in this case) would have been.

These points are in some sense moot because the survey strategy is basically set, and it will track anomalies accordingly. However, these anomalies are not necessarily noticed in the mode by which events are currently vetted, i.e., either manual or machine review of pipeline data, with tender-loving-care (TLC) re-reductions only for those events that “look interesting”. Consideration of the case of KMT-2019-BLG-0842 shows that very low- $q$  planets could give rise to long lived ( $\gtrsim 10$  hr) low-amplitude ( $\lesssim 0.1$  mag) “bumps” several mag below the peak of high-magnification events, which might easily escape the present search process. Hence, it would seem prudent to make TLC reductions of all high-mag events.

Moreover, there is a separate question as to how to marshal follow-up observations in order to probe to the lowest mass-ratio planets possible, i.e., planets of substantially smaller  $q$  than those that have been detected to date. At present, the rule of thumb is to intensively monitor high-magnification events within the FWHM around  $t_0$  because this

contains most of the sensitivity to planets. Specifically, “most” translates to a fraction  $\sim (\sec^{-1} 2)/(\pi/2) = 2/3$ . However, planets like KMT-2019-BLG-0842Lb lie in the other 1/3 of the circle. Although a minority, these planets give rise to long lived perturbations even when the planet has low mass ratio  $q$ , which can be of exceptional interest. Thus, particularly in very high-magnification events, for which  $t_{\text{eff}}$  is shorter, follow up observations at many  $t_{\text{eff}}$  are less expensive to carry out. Therefore, many- $t_{\text{eff}}$  observations should be more aggressively pursued in follow-up observations of these very high-magnification events.

## 6.2. Future High-Resolution Imaging and Spectroscopy

As discussed in Section 5.1, both the photometry and astrometry of the blended light make it broadly consistent with it being generated by the lens. This possibility could be tested with high resolution imaging, either with *Hubble Space Telescope* (*HST*) or ground-based adaptive optics (AO) on large telescopes. From Figure 5, the blended light is two magnitudes brighter than the source in the  $I$  band. Therefore, if *HST*  $I$ -band images showed that this blended light were closely aligned with the source position, then this would provide strong evidence that the blended light was due to the lens. In principle, such aligned light could be due to a stellar companion to either the source or the lens. However, if the alignment were very close (10–20 mas) then this would very likely rule out companions to the lens because these would have generated significant deviations over the well-covered peak of the event. And companions to the source could ultimately be ruled out by re-imaging the field when the source and blend had moved far enough apart to measure their relative proper motion. Because the source and blend have substantially different colors, such a measurement need not wait for the two stars to be separately resolved, but can be carried out via a measurement of the astrometric offset between their combined light in different bands (Bennett et al. 2006).

Ground-based AO astrometry could also test whether the blended light is aligned with the lens. The excess flux due to the blend would be somewhat more difficult to measure in this case because such measurements would be made in near-infrared bands (e.g.,  $H$  band), for which there are no direct measurements of the source flux. Nevertheless, based on  $VIH$  color-color relations of nearby field stars, derived from the KMT42 CMD (Figure 5) and the future AO measurements aligned to standard catalogs, it should be possible to predict the  $H$ -band source flux with reasonably good precision. Even though the blended light is much bluer than the source, it should still be substantially brighter in the  $H$  band than the source (because it is 2 mag brighter in the  $I$  band). Thus, ground-based AO measurements should be feasible.

The Bayesian posterior estimate of the lens-source relative proper motion is  $\mu_{\text{rel}} = 8.4^{+1.7}_{-1.2} \text{ mas yr}^{-1}$  (Table 3). Hence, to obtain a first measurement when the lens and source are still closely aligned, the observations should be made in 2020, if possible.

If the blended light proves to be aligned with the source, then it should be possible to spectroscopically classify the blend (Han et al. 2019). Such an observation might also plausibly measure the radial velocity (RV) offset between the source and the blend. If so, this would provide a second (and earlier) method to rule out the blend as being a companion to the source. Note that, to avoid generating a noticeable bump on the light curve, the blend (as companion) must have projected separation  $\gtrsim 8 \text{ AU}$  and so an RV offset of  $\lesssim 15 \text{ km s}^{-1}$  relative to the source.

If the blend proves not to be the lens (or, more precisely, not to be dominated by the lens light), then it should still be possible to characterize the lens with high-resolution followup. Depending on the flux and/or color differences between the source and the lens, this may be achieved even before the images are fully separated, e.g., by measuring the astrometric offset between the combined images in different bands (Bennett et al. 2006) or by measuring the elongation of the combined image (Bhattacharya et al. 2018). Even if the flux ratio is extreme, causing these combined-image techniques to fail, the lens can still be separately imaged when it has moved  $\sim 60 \text{ mas}$  (Batista et al. 2015) from the source, i.e., roughly by 2027. From Figure 7, the lens mass is almost certainly above the hydrogen-burning limit, so this method is almost guaranteed to work if all others fail.

In order to facilitate such future astrometric and photometric comparisons, we supply the KMT42 CMD with pixel positions and  $V$  and  $I$  instrumental magnitudes. The difference-image position of the source relative to this coordinate system is (150.60, 152.72).

W.Z. acknowledges support by the National Science Foundation of China (Grant No. 11821303 and 11761131004) Work by AG was supported by AST-1516842 from the US NSF and by JPL grant 1500811. AG received support from the European Research Council under the European Unions Seventh Framework Programme (FP 7) ERC Grant Agreement n. [321035] This research has made use of the KMTNet system operated by the Korea Astronomy and Space Science Institute (KASI) and the data were obtained at three host sites of CTIO in Chile, SAAO in South Africa, and SSO in Australia. Work by C.H. was supported by the grants (2017R1A4A1015178 and 2019R1A2C2085965) of National Research Foundation of Korea. The OGLE project has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to AU. The MOA project is supported by JSPS KAKENHI Grant Number JSPS24253004, JSPS26247023, JSPS23340064, JSPS15H00781, and JP16H06287. Work by CR was supported by an appointment to the

NASA Postdoctoral Program at the Goddard Space Flight Center, administered by USRA through a contract with NASA.

## REFERENCES

- Abe, F., Airey, C., Barnard, E. et al. 2013, MNRAS, 431, 2975
- Alard, C. & Lupton, R.H., 1998, ApJ, 503, 325
- Albrow, M. D., Horne, K., Bramich, D. M., et al. 2009, MNRAS, 397, 2099
- Batista, V., Beaulieu, J.-P., Bennett, D.P., et al. 2015, ApJ, 808, 170
- Beaulieu, J.-P. Bennett, D.P., Fouqué, P. et al. 2006, Nature, 439, 437
- Bennett, D.P. & Rhie, S.-H. 1996, ApJ, 472, 660
- Bennett, D.P., Anderson, J., Bond, I.A., Udalski, A., & Gould, A. 2006, ApJ, 647, L171
- Bensby, T. Yee, J.C., Feltzing, S. et al. 2013, A&A, 549A, 147
- Bessell, M.S., & Brett, J.M. 1988, PASP, 100, 1134
- Bhattacharya, A., Beaulieu, J.-P., Bennett, D.P., et al. 2018, AJ, 156, 289
- Bond, I.A., Udalski, A., Jaroszyński, M. et al. 2004, ApJ, 606, L155
- Bond, I.A., Bennett, D.P., Sumi, T. et al. 2017, MNRAS, 469, 2434
- Gaudi, B.S. 1998, ApJ, 506, 533
- Gould, A. 1992, ApJ, 392, 442
- Gould, A. 2000, ApJ, 542, 785
- Gould, A. 2004, ApJ, 606, 319
- Gould, A., Bennett, D.P., & Alves, D.R., ApJ, 614, 404
- Gould, A. & Loeb, A. 1992, ApJ, 396, 104
- Gould, A., Udalski, A., An, D. et al. 2006, ApJ, 644, L37
- Han, C., Yee, J.C., Udalski, A., et al. 2019, AJ, 158, 102



- Holtzman, J.A., Watson, A.M., Baum, W.A., et al. 1998, *AJ*, 115, 1946
- Hwang, K.-H., Udalski, A., Shvartzvald, Y. et al. 2018, *AJ*, 155, 20
- Jung, Y. K., Udalski, A., Gould, A., et al. 2018, *AJ*, 155, 219
- Jung, Y. K., Gould, A., Zang, W., et al. 2019, *AJ*, 157, 72
- Kervella, P., Thévenin, F., Di Folco, E., & Ségransan, D. 2004, *A&A*, 426, 297
- Kim, S.-L., Lee, C.-U., Park, B.-G., et al. 2016, *JKAS*, 49, 37
- Kim, D.-J., Kim, H.-W., Hwang, K.-H., et al., 2018a, *AJ*, 155, 76
- Kim, H.-W., Hwang, K.-H., Kim, D.-J., et al., 2018b, *AJ*, 155, 186
- Kim, H.-W., Hwang, K.-H., Kim, D.-J., et al., 2018c, AAS submitted, arXiv:1804.03352
- Kim, D.-J., Hwang, K.-H., Shvartzvald, et al. 2018d, arXiv:1806.07545
- Nataf, D.M., Gould, A., Fouqué, P. et al. 2013, *ApJ*, 769, 88
- Paczynski, B. 1986, *ApJ*, 304, 1
- Ryu, Y.-H., Udalski, A., Yee, J.C. et al. 2019b, AAS submitted, arXiv:1905.08148
- Shvartzvald, Y., Yee, J.C., Calchi Novati, S. et al. 2017, *ApJ*, 840, L3
- Suzuki, D., Bennett, D.P., Sumi, T., et al. 2016, *ApJ*, 833, 145
- Szymanski, M., Udalski, A., Soszyński, I., et al. 2011, *Acta Astron.*, 61, 83
- Tomaney, A.B. & Crotts, A.P.S. 1996, *AU*, 112, 2872
- Udalski, A., Szymanski, M.K., Soszynski, I., & Poleski, R. 2008, *Acta Astron* 58, 69
- Udalski, A., Szymanski, M.K., Szymanski, G., et al. 2015, *Acta Astron.*, 65, 1
- Udalski, A., Ryu, Y.-H., Sajadian, S., et al. 2018, *Acta Astron.*, 68, 1
- Woźniak, P. R. 2000, *Acta Astron.*, 50, 421
- Yoo, J., DePoy, D.L., Gal-Yam, A. et al. 2004, *ApJ*, 603, 139

Table 1. Binary Lens Models

Parameters	Close	Wide
$\chi^2/\text{dof}$	10065.4/10332	10241.5/10332
$t_0$ (HJD')	$8625.914 \pm 0.010$	$8625.914 \pm 0.011$
$u_0$ ( $10^{-3}$ )	$6.565 \pm 0.202$	$5.393 \pm 0.183$
$t_E$ (days)	$43.859 \pm 1.287$	$52.915 \pm 1.708$
$s$	$0.983 \pm 0.013$	$1.063 \pm 0.013$
$q$ ( $10^{-5}$ )	$4.079 \pm 0.289$	$3.901 \pm 0.249$
$\alpha$ (rad)	$0.146 \pm 0.067$	$0.144 \pm 0.072$
$\rho$ ( $10^{-4}$ )	$4.246 \pm 0.966$	$0.282^{+0.913}_{-0.090}$
$f_s$	0.037	0.030
$f_b$	0.179	0.185

Note. — HJD' = HJD – 2450000 days

Table 2. Binary Source Model

Parameters	1L2S
$\chi^2/\text{dof}$	10560.1/10031
$t_{0,1}$ (HJD')	$8625.907 \pm 0.013$
$u_{0,1}$ ( $10^{-3}$ )	$5.620 \pm 0.213$
$t_{0,2}$ (HJD')	$8627.886 \pm 0.032$
$u_{0,2}$ ( $10^{-3}$ )	$0.005 \pm 0.247$
$t_E$ (days)	$48.657 \pm 1.710$
$\rho_1$ ( $10^{-4}$ )	$7.6^{+16.0}_{-1.5}$
$\rho_2$ ( $10^{-4}$ )	$32.3 \pm 2.2$
$q_{F,I}$ ( $10^{-2}$ )	$1.291 \pm 0.043$
$f_s$	0.033
$f_b$	0.183

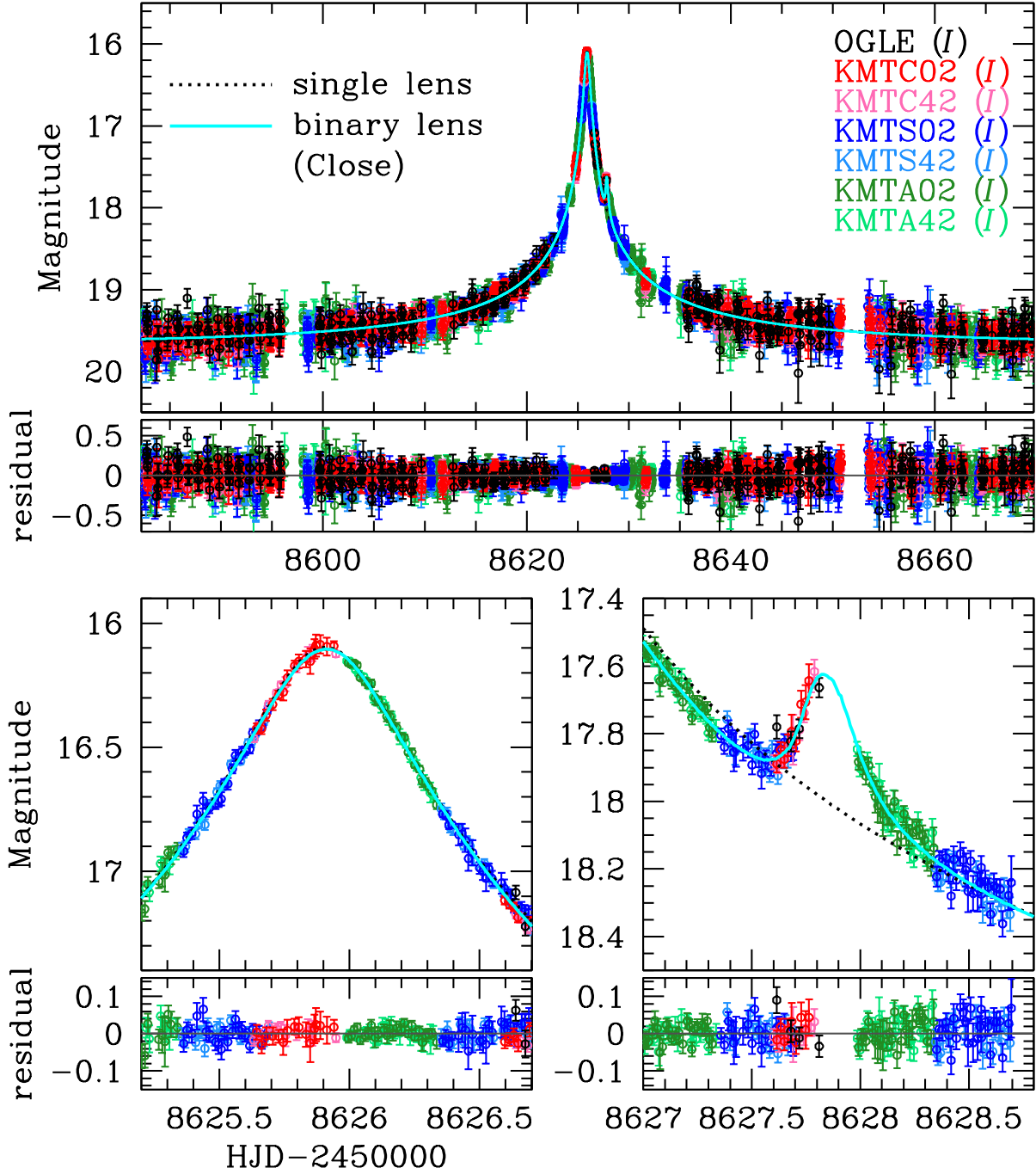


Fig. 1.— Light curve and “close” 2L1S model for KMT-2019-BLG-0842. Zooms of the peak and the anomaly are shown in the lower-left and lower-right panels, respectively. The anomaly lasts about 15 hours despite the very low planet-host mass ratio  $q = 4.1 \times 10^{-5}$  because the anomaly occurs  $\sim 7 \times t_{\text{eff}}$  effective timescales after peak, implying that the trajectory is at an acute angle  $\alpha \simeq \cot^{-1} 7 \sim 8.5^\circ$  relative to the planet-host axis.

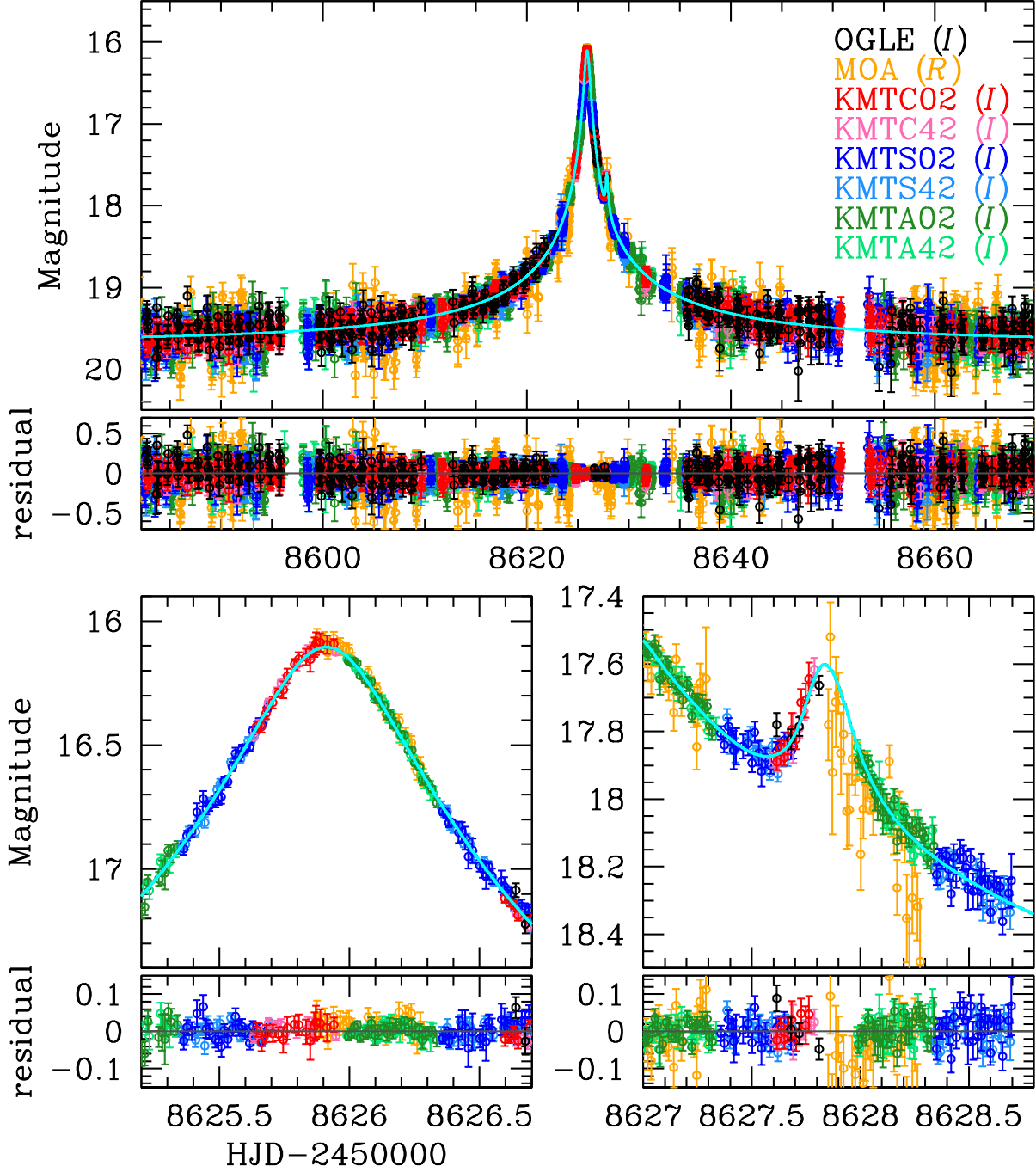


Fig. 2.— Light curve KMT-2019-BLG-0842, as shown in Figure 1, but with MOA data aligned to the best fit model. The MOA data confirm the anomaly but do not contribute to constraining the model and so are not included in the fit.

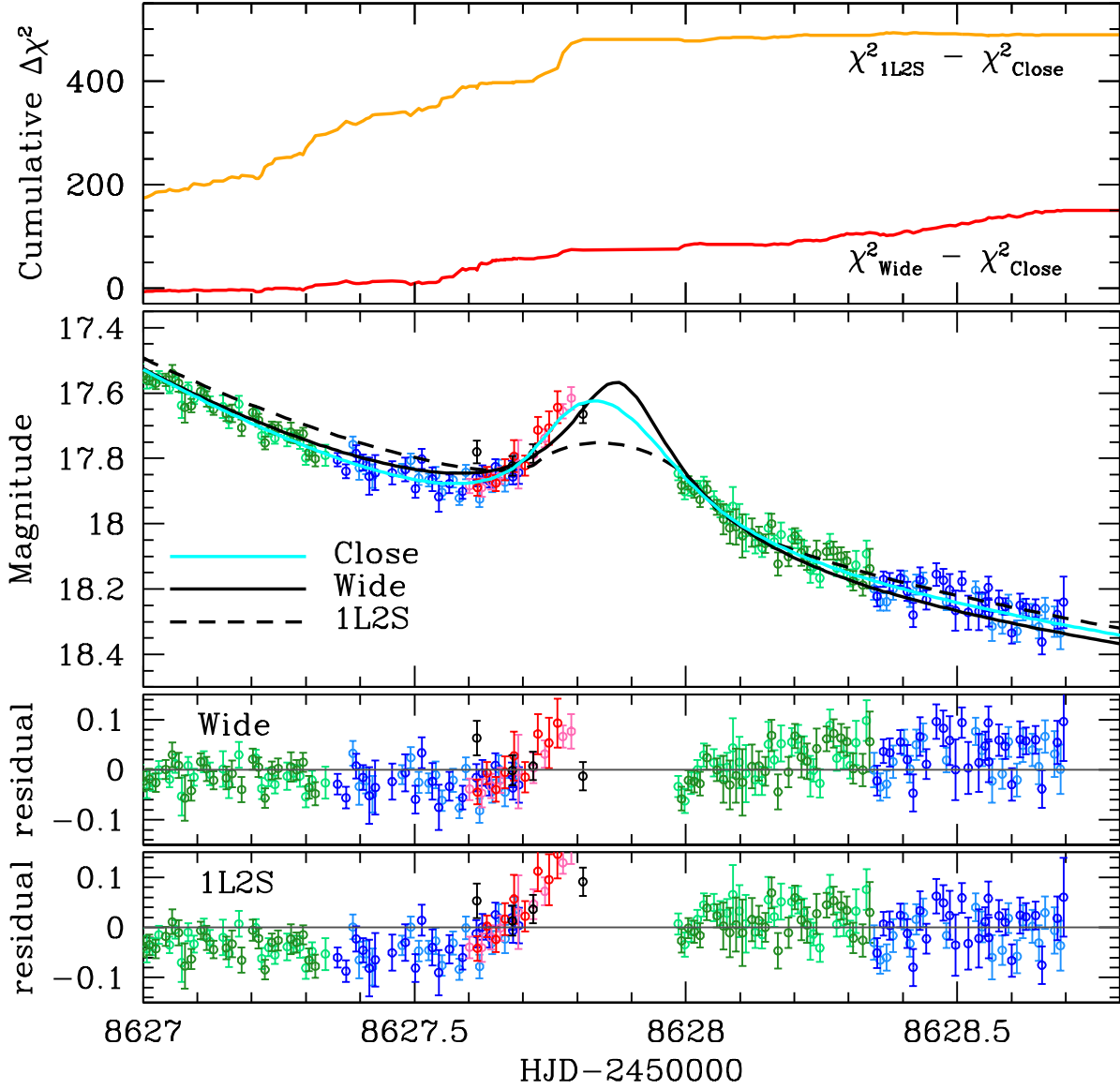


Fig. 3.— Upper panel:  $\Delta\chi^2$  difference relative to the only surviving model (2L1S “close”) of two other possible models, 2L1S “wide” (red) and 1L2S (yellow) for KMT-2019-BLG-0842. The second panel shows the anomaly region of the light curve together with these three models. The lower two panels show the residuals for the two excluded models. See Figure 1 for the corresponding residuals of the surviving (2L1S “close”) model.

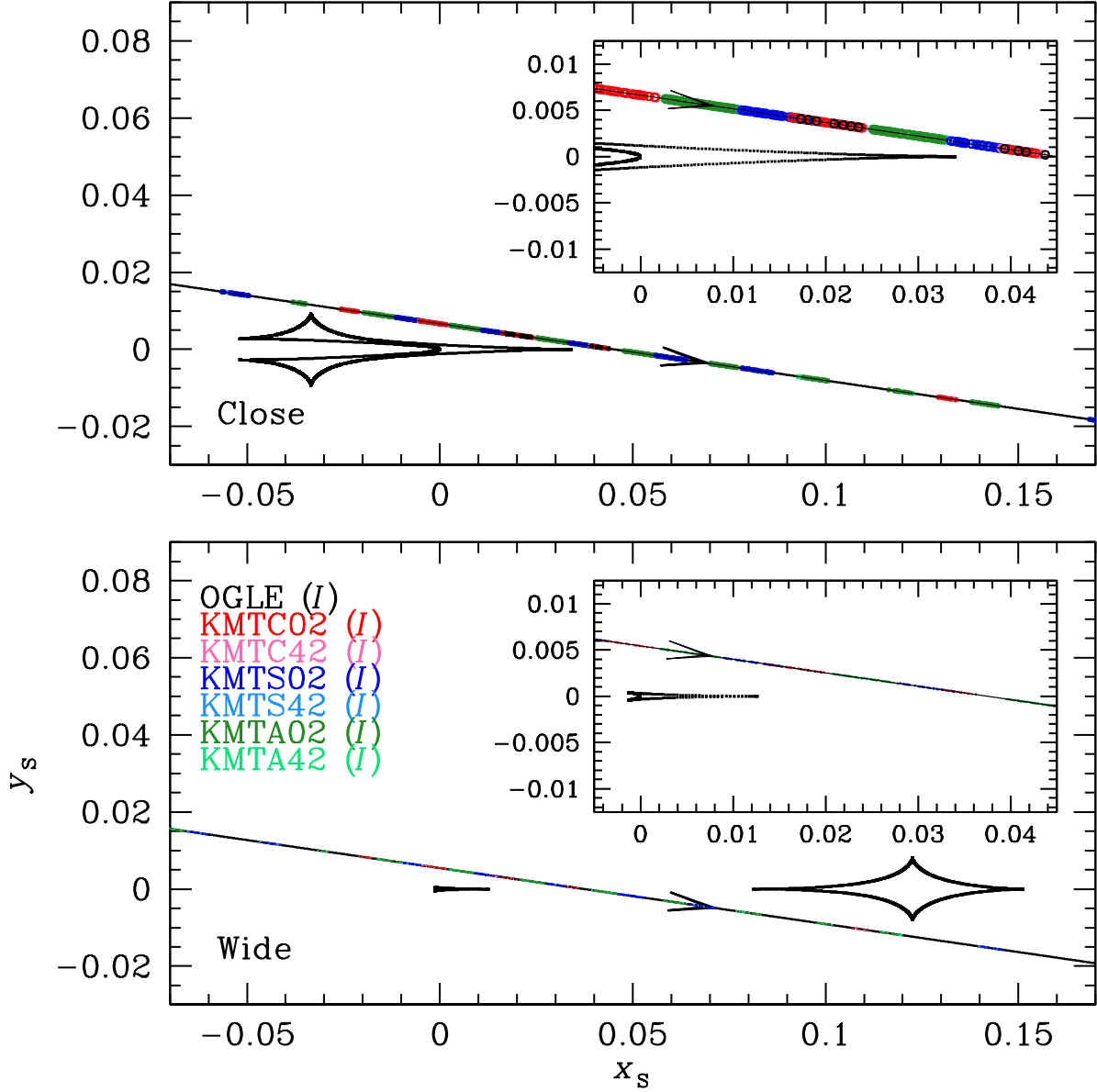


Fig. 4.— Caustic geometries for the two possible 2L1S solutions for KMT-2019-BLG-0842, i.e., “close” (top) and “wide” (bottom). In both cases, the anomaly (see zooms in Figures 1 and 3) is generated when the source passes over the planet-star axis about 1.94 days ( $\simeq 0.044$  Einstein units) after the peak. In both cases, the anomaly is due to a narrow high-magnification ridge that extends from the narrow end of a caustic centered on the host. For the “close” geometry, this caustic has a resonant (six-sided) topology, while for the “wide” geometry it is a central caustic that is connected to the planetary caustic by the ridge. However, the “wide” geometry is excluded by  $\Delta\chi^2 = 176$ . See text and Figure 3.

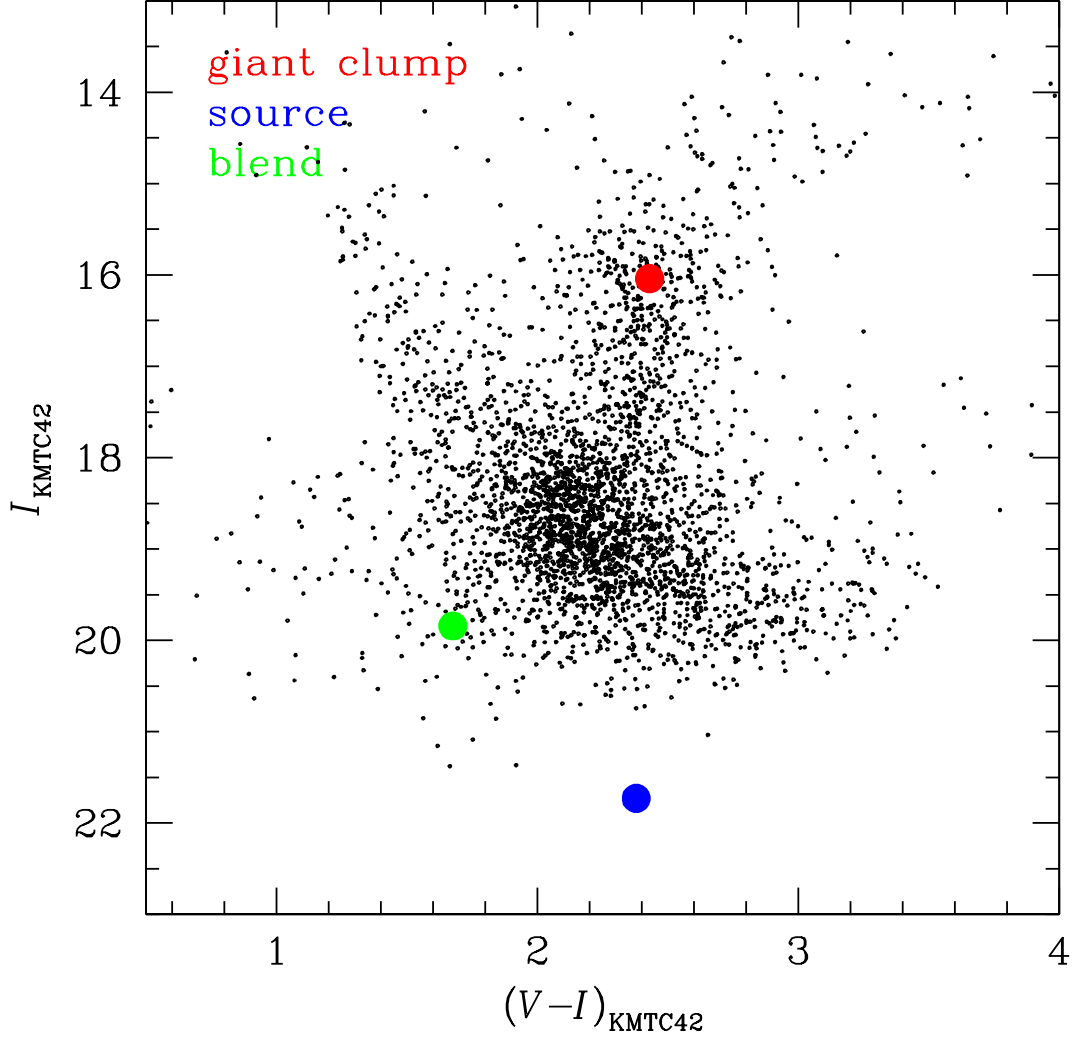


Fig. 5.— Color-magnitude diagram (CMD) for field stars in a  $2'$  square centered on KMT-2019-BLG-0842 derived from pyDIA reductions of KMTC42 data. The positions of the source (blue), the blend (green), and the centroid of the red clump (red) are indicated. The error bars for these determinations are discussed in the text. In particular, the blend color is relatively poorly determined. By cross-matching to the calibrated OGLE-III catalog (Udalski et al. 2008; Szymanski et al. 2011), we find  $I_{\text{calib}} = I_{\text{KMTC42C}} - 0.085$ ,  $(V - I)_{\text{calib}} = (V - I)_{\text{KMTC42C}} - 0.140$ .

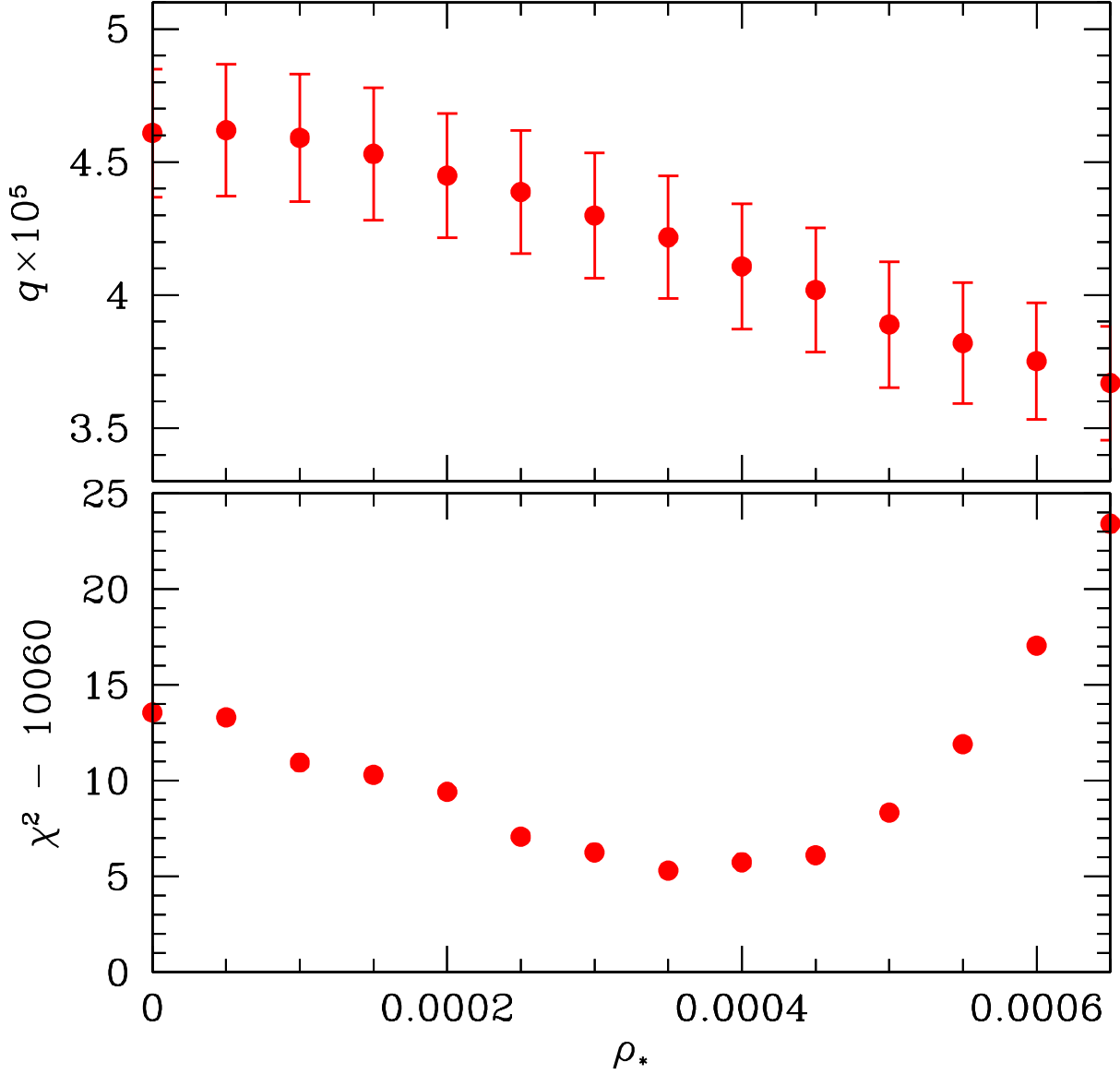


Fig. 6.— Lower panel: minimum values of  $\chi^2$  for a series of MCMC runs with the normalized source size  $\rho$  held fixed at the indicated values, each with 10,000 accepted elements on the chain. The minimum is overall relatively broad but high values (corresponding to small Einstein radii  $\theta_E = \theta_*/\rho$ ) are strongly ruled out. Upper panel: means and standard deviations of the planet-star mass ratio  $q$  for each of the MCMC runs carried out to make the bottom panel. Note that  $q$  is correlated with  $\rho$  over the broad  $\chi^2$  minimum of the latter. This correlation is taken into account in the Bayesian analysis (Section 5).



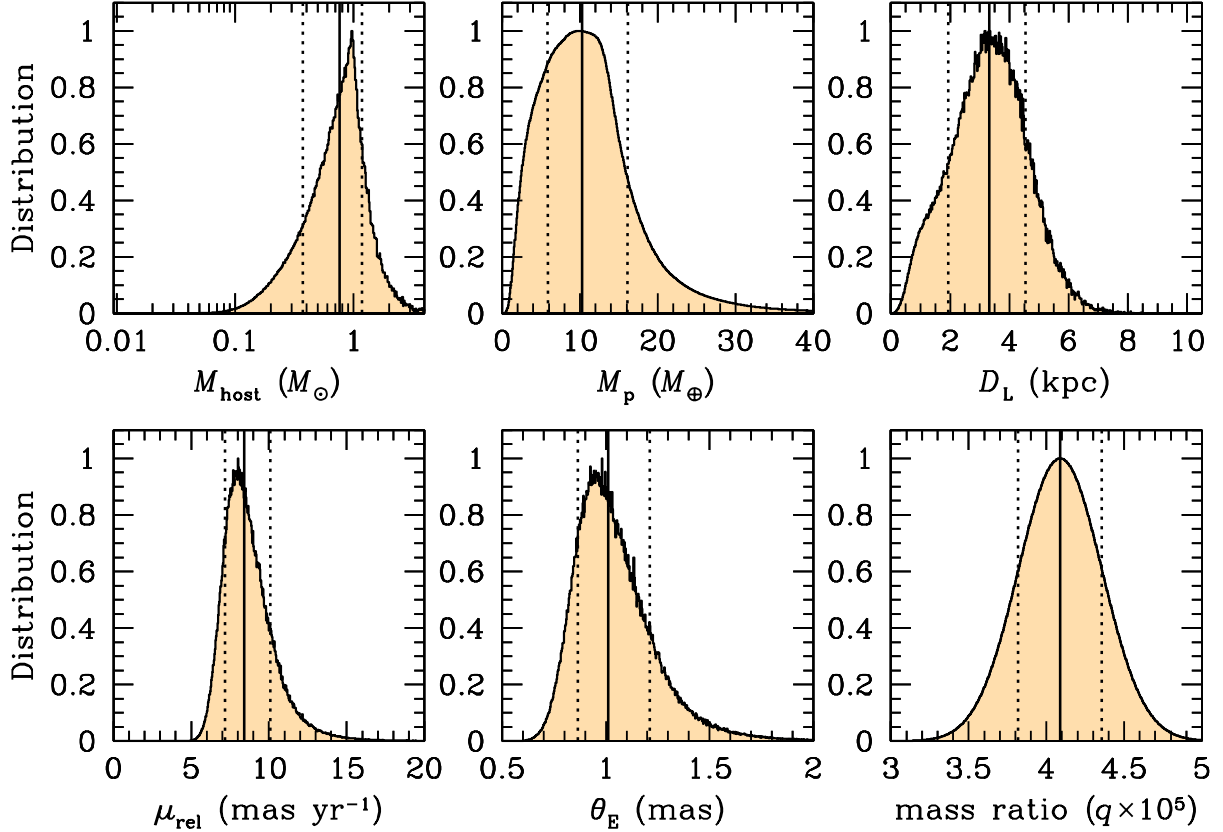


Fig. 7.— Bayesian posteriors for three physical parameters (host mass, planet mass, and system distance), along with three parameters that would normally be derived directly from the light curve and CMD (lens-source relative proper motion  $\mu_{\text{rel}}$ , Einstein radius  $\theta_{\text{E}}$ , and planet-star mass ratio  $q$ ). Bayesian posteriors are required for these three because  $\rho$  is relatively poorly determined and with significantly asymmetric errors. In particular,  $q$  is correlated with  $\rho$  (see Figure 6).

Table 3. Lens properties

Parameters	Values
$q$ ( $10^{-5}$ )	$4.09^{+0.26}_{-0.27}$
$\theta_{\text{E}}$ (mas)	$1.01^{+0.20}_{-0.15}$
$\mu_{\text{rel}}$ (mas yr $^{-1}$ )	$8.42^{+1.68}_{-1.24}$
$M_{\text{host}}$ ( $M_{\odot}$ )	$0.76^{+0.42}_{-0.39}$
$M_{\text{planet}}$ ( $M_{\oplus}$ )	$10.28^{+5.84}_{-5.28}$
$a_{\perp}$ (AU)	$3.31^{+1.38}_{-1.47}$
$D_{\text{L}}$ (kpc)	$3.32^{+1.22}_{-1.39}$